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Review

Field performance of a polymer electrolyte fuel cell for a residential energy system

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Abstract

This paper describes the performance evaluation of a polymer electrolyte fuel cell for application to a hybrid utilization experiment involving renewable energy and a fuel cell for a residential energy system. First, experiments on characteristics of heat and power generation were carried out. Direct current electrical efficiency and heat recovery efficiency for a rated output operation were quite high: 42.5 and 49.2%, respectively. Second, characteristics of partial load, water temperature for heat recovery, start-up time, load following and exhaust gas were clarified. Finally, measurement of characteristics of a hot water tank was carried out, and it was proved that sufficient performance can be obtained even under continuous operation.

Keywords: Residential energy system; Polymer electrolyte fuel cell; Electric power; Domestic hot water

Contents

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1. Introduction

In 2000, the domestic greenhouse gas emission in Japan was 1332 million tons of CO_2, an increase of 8% in comparison with that of 1990. If the Kyoto Protocol to the United Nations Framework Convention on Climate Change (COP3) held in December 1997 comes into effect, Japan comes under the obligation to reduce emission by 6% compared with the 1990 values. As a result, Japan is required to reduce emission by 14% (172 million tons) on average during the period between 2008 and 2012. Particularly, emission in the residential/commercial sector in 2000 increased by 21.3%, compared with that of 1990. More effort is needed regarding emission control for housing and buildings. In this situation, the energy-saving characteristics of polymer electrolyte fuel cells (PEFCs) and proton exchange membrane fuel cells (PEMFCs) have attracted attention in cogeneration system (CGSs), contributing to the effective use of energy.

Technical development of PEFCs has been in progress in Japan and abroad due to its practical advantages: PEFCs have such characteristics as ability to function at low temperatures, comparatively easy start-up and stop, high overall energy efficiency, low pollution and noiselessness [1–7]. Especially in Japan, these technical developments have been promoted by such organizations as the Ministry of Land, Infrastructure and Transport [8], the Ministry of Economy, Culture, Sports, Science and Industry [9], the Japan Gas Association [10] and the Fuel Cell Commercialization Conference of Japan (FCCJ) (secretariat: New Energy Foundation) [11].

In terms of the appropriate operation of fuel cells for residential use, much research has been carried out so far [12–22]. Through these analyses, the energy-saving effect was

confirmed. However, quite a few feasibility evaluations based on the detailed operation performance of prototypes as regards power generation and heat recovery efficiency were carried out.

The authors' laboratory carried out continuous studies on low energy homes with hybrid utilization of renewable energy [23–25]. In these studies, the target levels of utilization of renewable energy for super-insulated and airtight homes were determined. Various combinations of experiments were carried out at an experimental house built on the campus of Hokkaido University, Japan. Based on the long-term operation performance, its effectiveness was measured. In addition, numerical analyses on the characteristics of usage of a variety of renewable energy source in low energy homes and the feasibility of usage were carried out. The annual energy balance and possible application to other regions were studied. Based on the payback periods of various technologies and life cycle analyses, overall evaluations were carried out. As for the prospect of the diffusion of low energy homes, it is indispensable that the utility base of renewable energy be gradually reinforced. Therefore, the development of hybrid utilization of renewable energy and advanced conventional energy sources, including fuel cell cogeneration systems, is thought to be urgent.

This research aims at the hybrid utilization of renewable energy and fuel cells for a residential energy system. Performance evaluation of the PEFC for application to the demonstration project was carried out. First, the specifications of a PEFC prototype with a generating capacity of 1 kW and experimental equipment are described. Second, the characteristics of partial load, water temperature for heat recovery, start-up time, load following and exhaust gas are clarified. Finally, the measurement of characteristics of a hot water tank and the performance under continuous operation was carried out.

2. Specifications of the PEFC

Fig. 1 and Table 1 show the physical appearance and specifications of the fuel cell cogeneration system used in this study. The fuel cell type of this prototype is PEFC. The fuel cell cogeneration unit itself is a built-in package consisting of a reformer, a heat recovery device, an inverter, grid-connected system equipment and auxiliary equipment (pumps and a blower) as well as a fuel cell stack. The generating capacity for a rated output operation is 1 kW with AC, and partial load operations are also available at 75 and 50%. The thermal output (60 °C) is supplied to a hot water tank. The effective capacity of the hot water tank is 200 l. Utilities are city water, commercial electric power (grid-connected system) and natural gas. Fig. 2 shows an overview of the fuel cell cogeneration system. Natural gas is used for warming the reformer at start-up. When the temperature becomes stable, natural gas is reformed into hydrogen (fuel gas), and supplied to the cell stack. Water for vapor reforming can be obtained by recovering the water produced in the fuel cell stack. Heat recovery water from the stack and exhaust gas is supplied from the bottom of the hot water tank and discharged to the top of the tank after heat recovery.

Fig. 1. Physical appearance of the PEFC.

3. Overview of experiments on heat and power generation characteristics

3.1. Experimental equipment and measurement system

Fig. 3 and Table 2 show the system of experimental equipment, and the items and equipment for measurement. The temperature of the hot water tank was controlled by

Table 1
Specification of PEFC

Fuel cell type	Polymer electrolyte fuel cell
Stack specification	Integrated humidifier (filter type)
Dimensions	0.9 m (*W*), 0.46 m (*D*), 1.1 m (*H*)
Raw fuel (natural gas)	Maximum 10 Nl/min (1.47–1.63 kPa)
Raw fuel supply method	Outside reformer
Feed water	Maximum 10 Nl/min (100–300 kPa)
Electricity	Single-phase three-wire distribution system
Maximum output	1 kW (AC)
Water temperature for heat recovery	60 °C (outlet temperature)
Volumetric flow rate for heat recovery	Maximum 2 l/min
Water tank volume	200 l

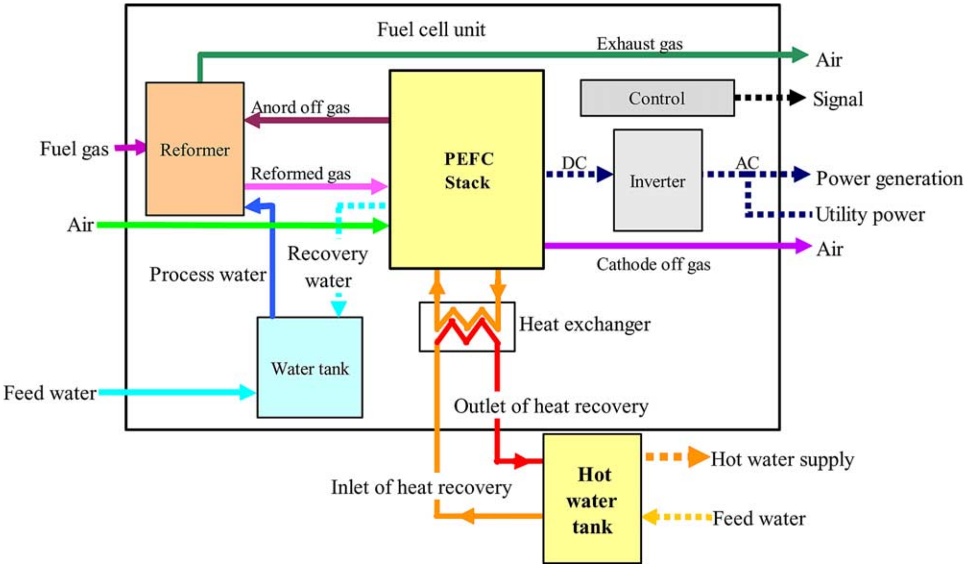

Fig. 2. Overview of the fuel cell cogeneration system.

a radiator placed outdoors. The measuring apparatus for gas flow rate and temperature, generated power (DC/AC) and water flow rate and temperature for heat recovery were built into the fuel cell unit. A personal computer recorded all the data every 10 s. Measurements with a gas flow meter, a wattmeter, a flow-meter and thermometers were

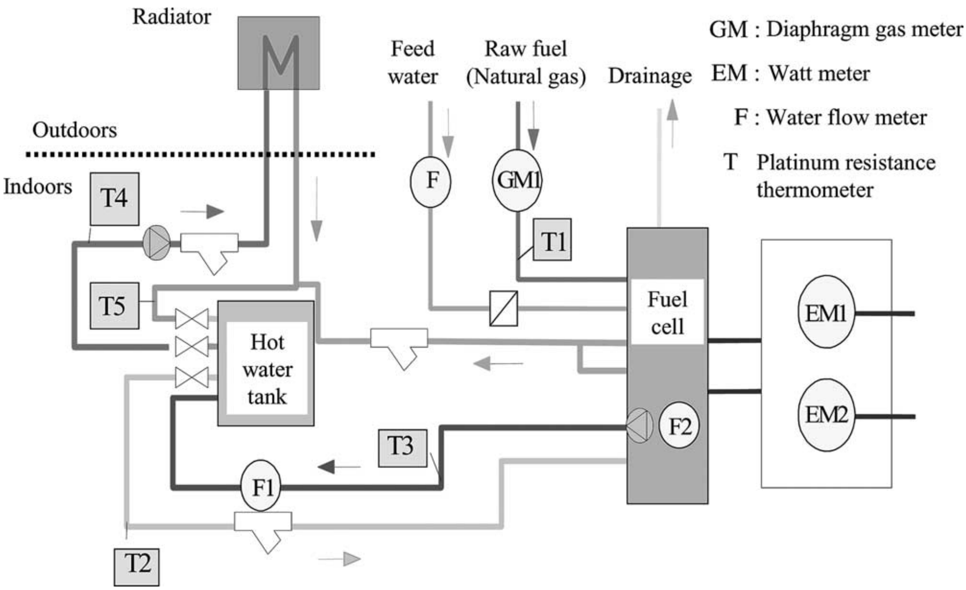

Fig. 3. System diagram of experimental equipment.

Table 2
Measurement items and measuring equipment of experiments on heat and power generation characteristics

Measurement item	Measuring equipment
Temperature	Platinum resistance thermometer
Water flow rate	Volumetric flow meter
Raw fuel consumption	Diaphragm gas meter
Drainage	Graduated cylinder
Exhaust gas (CO)	Measuring apparatus for exhaust gas of burner
Exhaust gas (NO_x)	Chemiluminescent NO_x analyzer

carried out outside the unit by a data logger every minute. Drainage volume and components of exhaust gas were appropriately measured in order to evaluate the environmental impacts.

3.2. Experimental conditions

Table 3 shows the experimental conditions. For a fixed output operation (load factor: 50, 75 and 100%) from cold start and hot start, respectively, measurement of characteristics of power generation and heat recovery was carried out. The load following performance was also evaluated. The inlet temperature of the heat recovery water was set in the range of 5–30 °C. The effect of inlet/outlet temperature of heat recovery water on power generation efficiency and heat recovery efficiency was investigated.

Table 3
Experimental conditions of characteristics of heat and power generation

Operation	Load factor (%)	Water temperature for heat recovery (°C)
Fixed output		
Cold start	50	15
	75	20
	100	5
		20
		30
Hot start	50 → 0 → 50	20
	50 → 0 → 100	20
	75 → 0 → 75	15
	100 → 0 → 50	15
	100 → 0 → 100	10
	100 → 0 → 100	32
Output change		
	50 → 75 → 100	20
	50 → 100 → 50	20
	100 → 75 → 50	25

4. Experimental results of power generation and heat recovery

4.1. Rated output operation

The performance of power generation for a rated output operation (cold start) on October 16, 2001, is shown in Fig. 4. The inlet temperature of the heat recovery water was approximately 22 °C. The operation time was 9 h and 12 min. Fuel (natural gas) is used for heating both reformer and cell stack from start-up to the beginning of power generation. The average direct current generating output during the rated output operation was 1475 W. The direct current electrical efficiency at low heating value (LHV) was quite high: 42.2%. The generating output of the AC inverter and net power were 1231 and 997 W, respectively. The net electrical efficiency at LHV was 28.3%. Almost no change in electrical efficiency was seen under continuous operation, as shown in Fig. 4. Fig. 5 shows the variation of the thermal output of heat recovery and inlet/outlet temperature. The average outlet temperature during the rated output operation was 61.1 °C. Sufficient hot water was obtained for domestic supply. The thermal output of heat recovery was stable at approximately 1730 W. Table 4 shows the operation performance of rated output operations during the experimental period. The average net power and heat recovery outlet temperature were 999 W and 61.2 °C, respectively. The designed performance was almost obtained. The standard deviation of net power was quite low: 3.7. Stable performance was proved. Direct current electrical efficiency and heat recovery efficiency at LHV were quite high: 42.5 and 49.2%, respectively. The overall energy efficiency reached 77.9%.

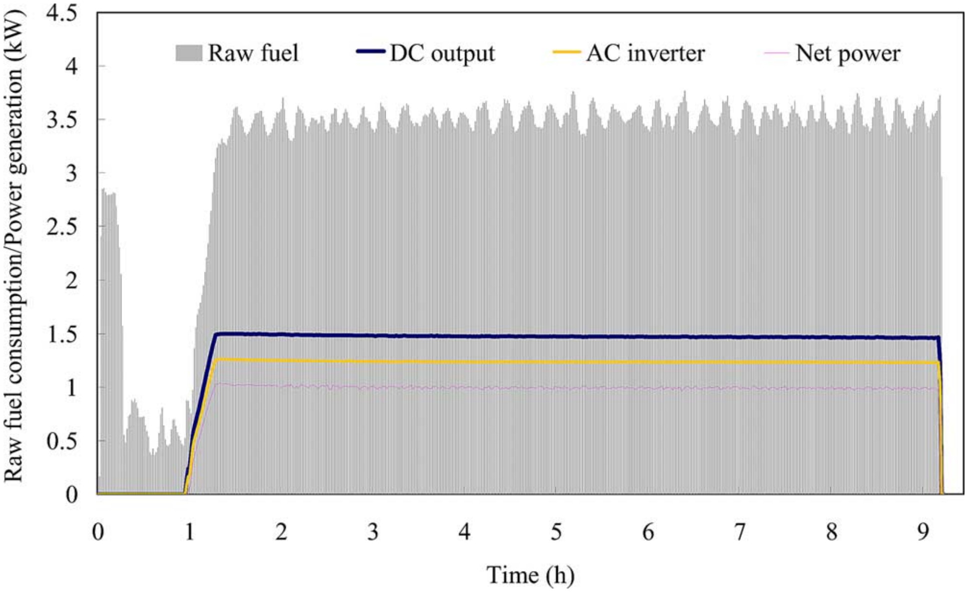

Fig. 4. Power generation for rated output operation on October 16, 2001.

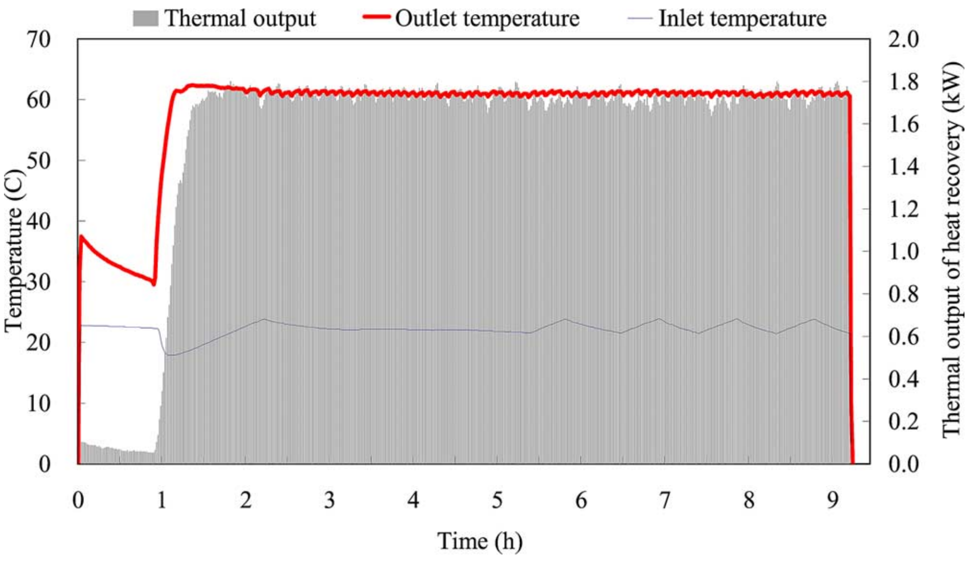

Fig. 5. Thermal output of heat recovery and water temperature for rated output operation on October 16, 2001.

Table 4
Operation performance for rated output operations[a]

Operation performance	Mean	Maximum	Minimum	Standard deviation
Raw fuel consumption (NL/h)	300.7	302.8	296.7	2.0
DC output (W)	1477.1	1487.2	1462.0	7.6
Net power (W)	998.5	1004.3	989.5	3.7
Thermal output of heat recovery (W)	1709.7	1770.5	1590.7	55.1
Inlet water temperature (°C)	22.4	22.7	21.6	0.3
Outlet water temperature (°C)	61.2	62.2	60.6	0.3
Temperature difference (°C)	38.8	40.0	37.9	0.5
Water flow rate (l/min)	0.6	0.7	0.6	0.0
DC electrical efficiency (%)	42.5	43.0	42.0	0.2
Net electrical efficiency (%)	28.7	29.0	28.4	0.2
Heat recovery efficiency (%)	49.2	51.5	46.4	1.5
Overall energy efficiency (%)	77.9	80.5	75.4	1.6

[a] The data for 1 h immediately after reaching the rated output were excluded. The mean shows the hourly average after that.

4.2. Characteristics of partial load

Fig. 6 shows the effect of load factor affecting power generation and heat recovery efficiency. Net power at the load factor of 50 and 75% was a little higher than the set values: 538 and 779 W, respectively. The efficiency of the cell stack was excellent at low partial load. The lower the load factor became, the higher direct current electrical efficiency rose. On the other hand, the larger the output became, the higher the efficiency of the reformer rose. And the electric power required for auxiliary equipment became smaller. As a result, there was not much difference in net electrical efficiency at each load factor.

4.3. Effect of inlet water temperature for heat recovery

Fig. 7 shows the effect of inlet water temperature for heat recovery (5–30 °C) on power and heat recovery efficiency for a rated output operation. The lower the inlet water temperature became, the higher by a small amount the heat recovery efficiency rose. The difference in efficiency was proved to be approximately 2% between 10 and 30 °C. On the other hand, electrical efficiency was almost stable whatever the inlet water temperature for heat recovery.

4.4. Characteristics of start-up and load following

Fig. 8 shows the characteristics of cold start and hot start of PEFC. Start-up time depends on the temperature conditions of the reformer. It took 60 min for cold start

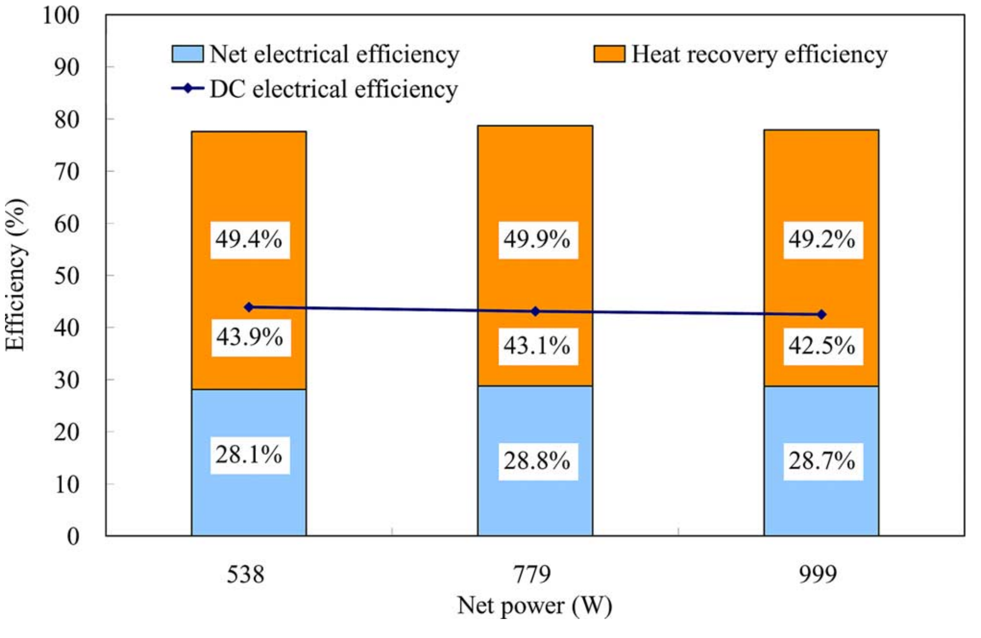

Fig. 6. Effect of load factor affecting power generation and heat recovery efficiency.

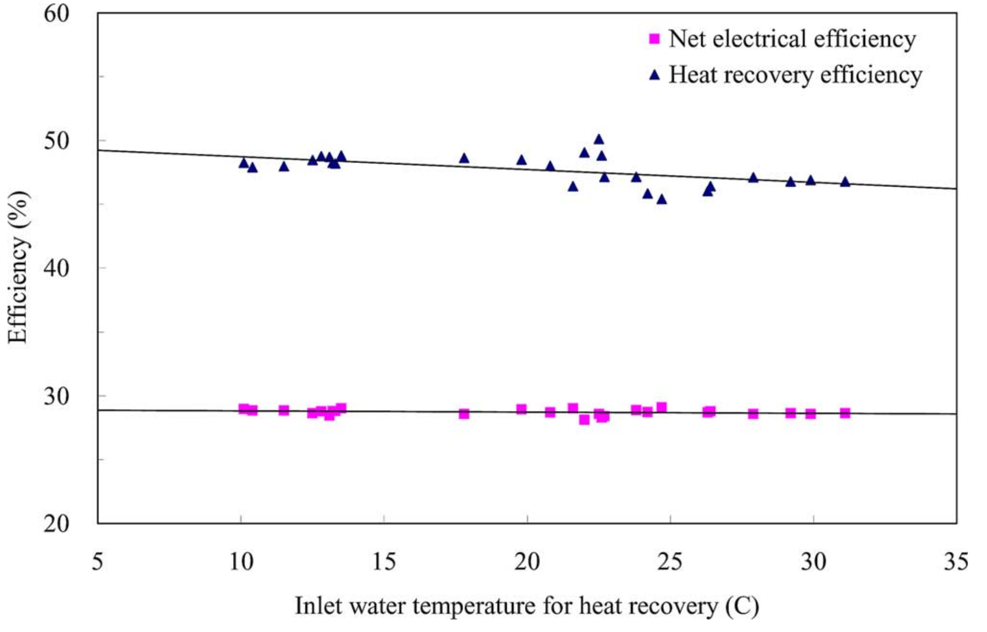

Fig. 7. Effect of inlet water temperature for heat recovery in power generation and heat recovery efficiency for rated output operation.

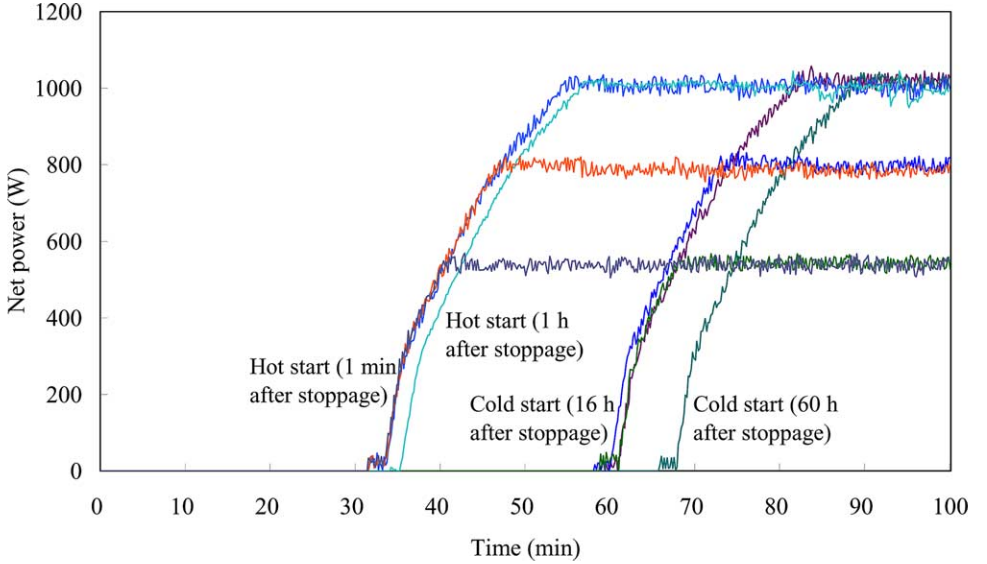

Fig. 8. Characteristics of cold start and hot start of PEFC.

(approximately 16 h after operation stoppage) and 32 min at hot start (approximately 1 min after operation stoppage). It took a further 28 min to reach 1 kW. Table 5 shows the load following characteristics. The transition time increased as the output changes to a higher load factor. The maximum time was approximately 10 min for the transition of load factor from 50 to 100%. On the other hand, it was only 2 min from 100 to 50%.

4.5. Measurement of environmental impact

Measurement of exhaust gas for a rated output operation (1 kW) showed NO_x, CO_2 and O_2 to be 4.8 ppm, 19.1 and 4.2%, respectively. The NO_x emission in the exhaust gas was quite low, which proved that this system has low environmental impact.

5. Overview of experiments on power and domestic hot water system

5.1. Experimental equipment and measurement system

Experiments on power and the domestic hot water system were carried out at a low energy house on the campus of Hokkaido University, Japan [24]. Fig. 9 shows the experimental equipment system. Fuel for the PEFC was supplied by a compressed natural gas (CNG) cylinder. Table 6 shows the list of items and equipment for measurement. Measurements from each of the equipment in the PEFC unit were recorded every 10 s on a personal computer. Measurements using a gas flow meter, a wattmeter, a flowmeter and thermometers were carried out outside the unit by a data logger every 10 s.

5.2. Experimental conditions

Table 7 shows the schedule and experimental conditions. The initial water temperature of the hot water tank was set at approximately 15 °C in the experiment on power and heat recovery characteristics at each load factor. In this paper, applicability to domestic hot water systems was emphasized. The thermal stratification characteristics of the tank, thermal performance and characteristics of continuous operation (over 24 h) were examined. Moreover, energy saving, environment conservation and economic benefit were evaluated in comparison with conventional utility power and domestic hot water systems using gas boiler.

Table 5
Load following characteristics of PEFC

Output change	Load factor (%)		Transition time
	Before	After	
Decrease	100	75	1 min 30 s
	75	50	1 min 10 s
	100	50	2 min 00 s
Increase	50	75	3 min 15 s
	75	100	4 min 40 s
	50	100	9 min 30 s

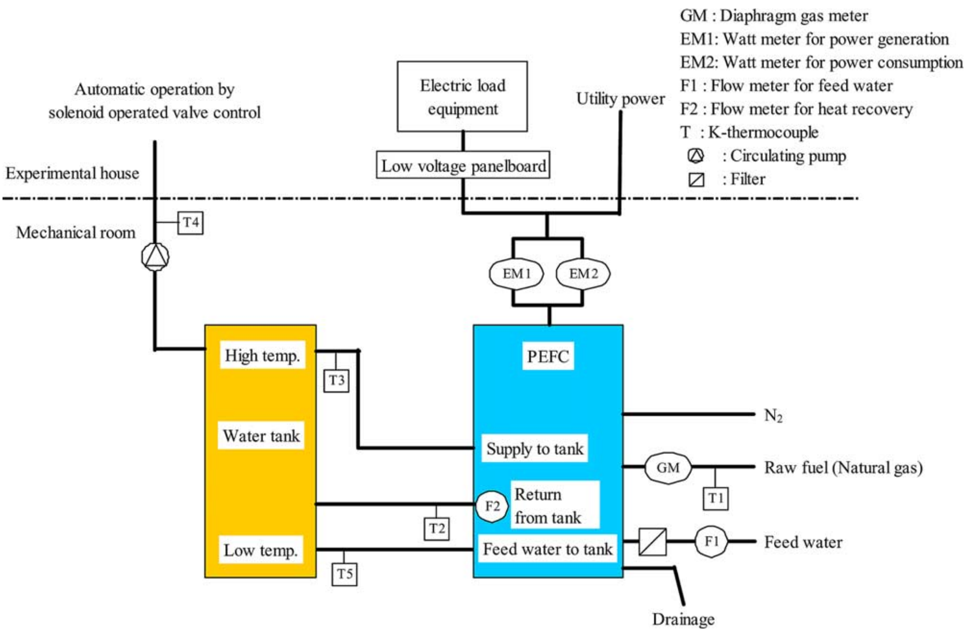

Fig. 9. Experimental equipment system.

6. Results and discussion on power and domestic hot water system

6.1. Operating results for a rated output operation and thermal performance

Figs. 10 and 11 show the temperature fluctuations of heat recovery water, water tank and ambient and the temperature distribution in the tank on December 11, 2001

Table 6
Measurement items and measuring equipment of experiments on power and domestic hot water system

Measurement item	Measuring equipment
Raw fuel gas flow rate	Measuring apparatus built in PEFC unit
Generated power (DC/AC)	
Water flow rate and temperature	
Raw fuel consumption	Diaphragm gas meter
Net power/power consumption	Wattmeter
Water temperature in tank	K-thermocouple
Fuel gas temperature	Sheathed-type K-thermocouple
Feed water temperature	
Hot water supply temperature	
Hot water consumption	Volumetric flowmeter
Drainage	Graduated cylinder
Exhaust gas temperature/humidity	Thermistor and macromolecule Humidity sensor
Ambient temperature/humidity	

Table 7
Schedule and conditions for experiments on power and domestic hot water system

Schedule	Load factor (%)	Evaluation items
December 11, 2001	100	Characteristics of heat and power generation. Thermal stratification characteristics in hot water tank
December 12–14, 2001		Heat loss from hot water tank
December 16, 2001	75	Characteristics of heat and power generation.
December 17, 25, 2001	50	Thermal stratification characteristics in hot water tank
January 9–12, 2002	100	Continuous operation (48 h)
February 18–19, 2002	75	Continuous operation (24 h)
January 24–25, 2002	50	Continuous operation (24 h)

(load factor of 100%), respectively. There were five measurement points of vertical temperature distribution in the tank. Fig. 10 shows the value at each of the five layers in terms of the distance from the bottom; first 921 mm, second 741 mm, third 561 mm, fourth 381 mm and fifth 21 mm. The operation was finished in 7 h and 12 min, when the heat storage was saturated and the heat recovery inlet temperature reached 40 °C. The mean ambient temperature during the operation was 14.4 °C. The heat recovery outlet temperature was stable at around 62 °C. It took the second layer's water temperature 2 h and 48 min to reach 45 °C for domestic hot water. The water temperature in the third layer reached 45 °C in 4 h 3 min. and in the fourth layer, in 6 h 22 min. The thermal stratification was relatively good. Figs. 12 and 13 show

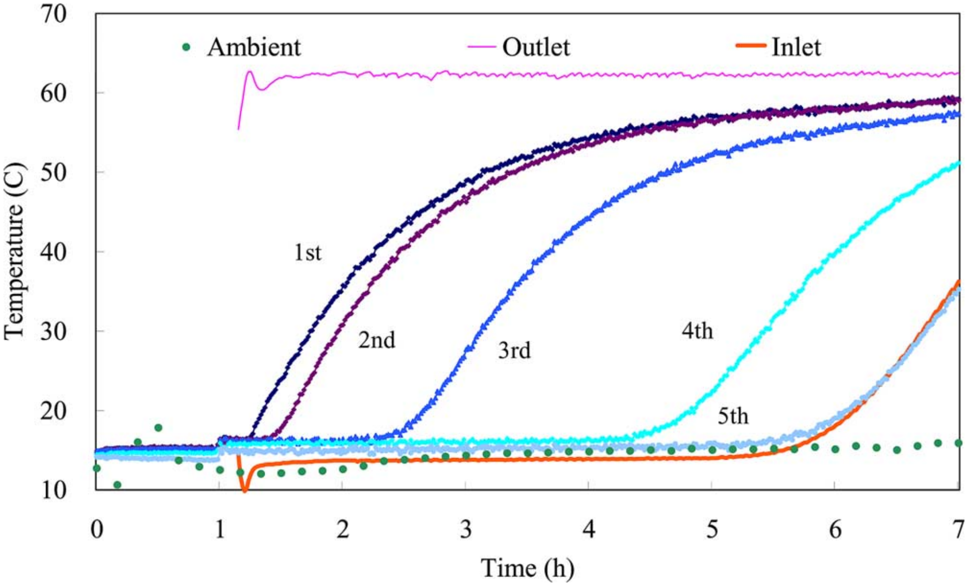

Fig. 10. Temperature fluctuations of heat recovery water, water tank and ambient (load factor of 100%).

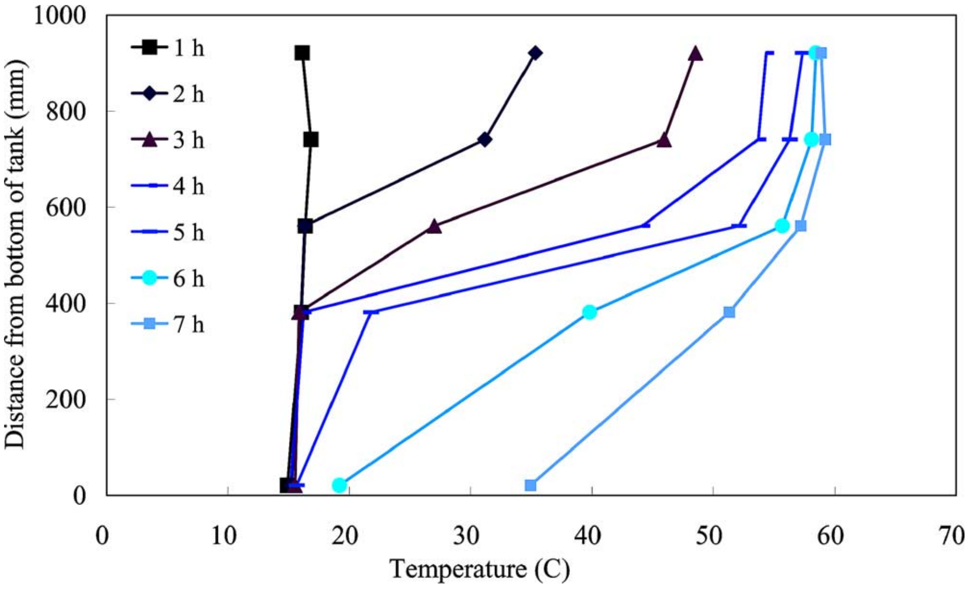

Fig. 11. Temperature distribution in water tank (load factor of 100%).

the temperature distribution and thermal performance, respectively, after the stoppage of operation. Even 10 h after stoppage, 45 °C was still maintained in the upper three layers. The temperature difference between the third and the fifth layer was approximately 18.6 °C. The thermal loss thus far was 6.95 MJ (thermal loss factor:

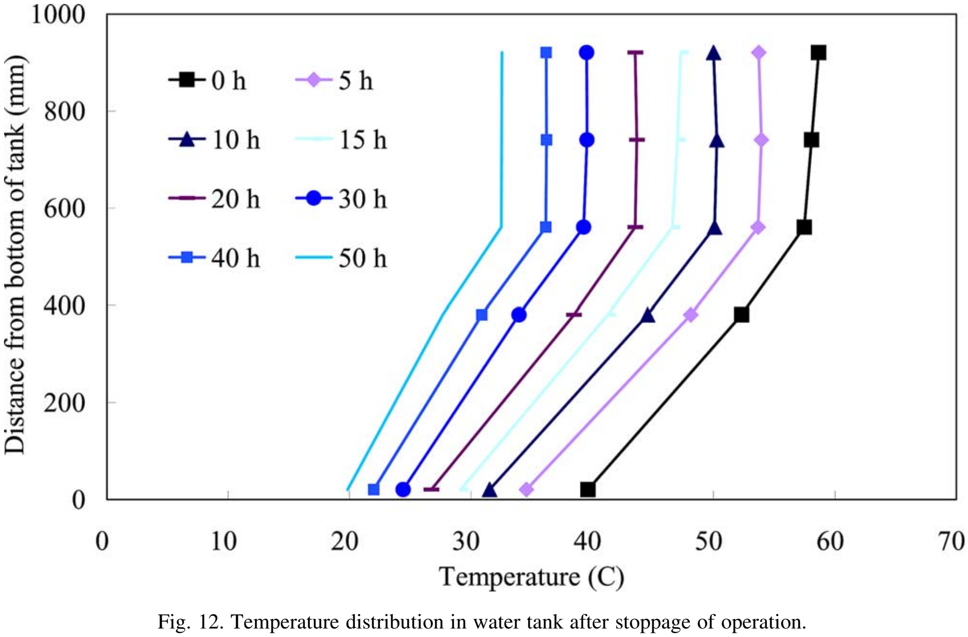

Fig. 12. Temperature distribution in water tank after stoppage of operation.

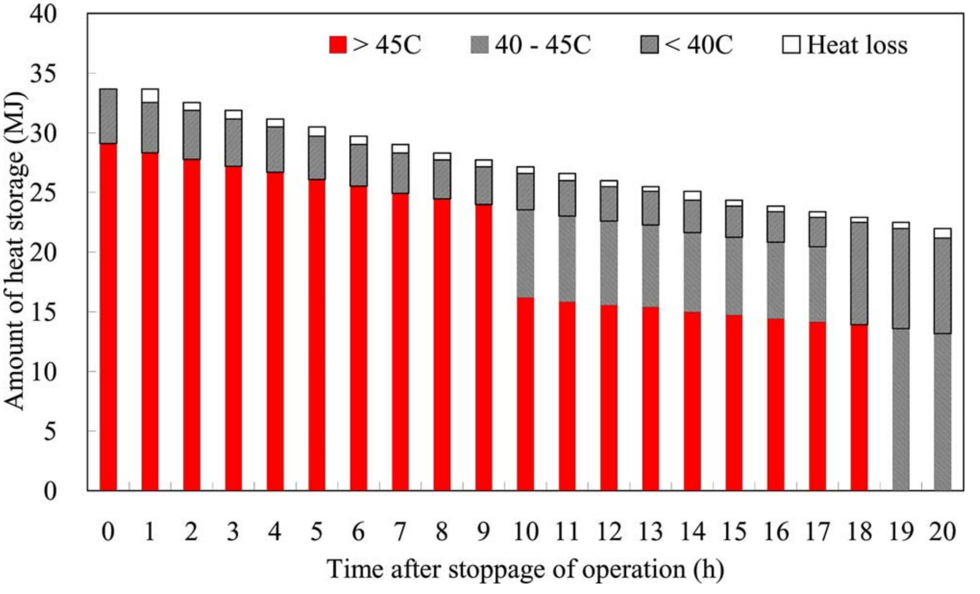

Fig. 13. Thermal performance of water tank.

about 2%/h). The reduction of amount of heat over 40 °C was approximately 19.1%. The average ambient temperature outside the tank was around 20 °C. The coefficient of the heat loss from the tank (GW24K: 25 mm) was 3.1 W/m^2 K.

6.2. Characteristics of partial load and continuous operation

The characteristics of heating a hot water tank were evaluated for a power generating output of load factors of 50 and 75% as well as rated output operation. Table 8 shows the operation performance for each load factor. It took the thermal storage approximately 9 h

Table 8
Operation performance at each load factor

Load factor (%)	50	75	100
Operation time (h:min)	11:20	8:58	7:12
DC output (MJ)	30.3	33.1	32.1
Net power (MJ)	19.0	21.3	20.4
Thermal output of heat recovery (MJ)	35.0	37.0	36.6
Outlet water temperature (°C)	60.5	60.9	62.3
Thermal loss (MJ)	2.9	5.0	2.3
Stored thermal energy (>45 °C) (MJ)	27.6	27.6	29.8
Stored thermal energy (40–45 °C) (MJ)	0.0	0.0	0.0
Stored thermal energy (<40 °C) (MJ)	4.5	4.4	4.6
Ambient temperature (°C)	16.0	11.7	14.4

Table 9
Characteristics of power generation and heat recovery under continuous operation[a]

Load factor (%)	50	75	100
Operation time (h)	24	24	48
Interval of draining hot water (h)	8	6	4
Amount of draining hot water (L)	240	300	300
DC output (MJ/h)	2.97	4.10	5.13
Net power (MJ/h)	1.87	2.64	3.23
Thermal output of heat recovery (MJ/h)	3.47	4.65	6.10
Outlet water temperature (°C)	60.81	61.42	63.59
Ratio of DC electrical efficiency (%)	0.98	0.99	0.98 (0.96)
Ratio of net electrical efficiency (%)	0.97	0.99	0.96 (0.93)
Ratio of heat recovery efficiency (%)	1.03	1.04	0.98 (1.00)

[a] Each ratio of efficiency shows the ratio of the value after 24 h to the value at the beginning of power generation. Bracketed values at the load factor of 100% show the ratios after 48 h.

at load factor 75% and 11 h and 20 min at 50% to be saturated. The reduction rate of primary energy, CO_2 and cost were 21.3, 18.8 and 29.4%, respectively (conventional system: utility power 9.887 MJ/kW h, 0.131 kg-C/kW h, 23.5 yen/kW h; natural gas boiler 0.664 kg-C/m^3, 92 yen/m^3) [26–30]. Table 9 shows the characteristics of power generation and heat recovery under continuous operation. The last three rows of Table 9 show the ratios of efficiency, i.e. the ratios of the values after 24 h to the values at the beginning of power generation. The ratio of direct current electrical efficiency was over 0.98 for every load factor. It was proved that stable performance could be obtained. For a load factor of 100%, it was 0.96 even after 48 h. Direct current electrical efficiency decreased only by 5% of the initial value after a cumulative operation time of about 600 h. Therefore, no excessive deterioration was seen.

Considering the circumstances mentioned above, the high energy-saving performance and environment friendliness of the system were confirmed. Fuel cell technology has been positively developed centering on producers of electric appliances and automobiles. Therefore, the performance can be upgraded. Several characteristics clarified in the experiments show possibilities for the development of the fuel cell for residential energy systems in the future as follows:

(1) Improvement of net electrical efficiency. In addition to the improvement of both stack and fuel reforming efficiencies, net electrical efficiency should be improved by the exclusive design of the auxiliary equipment and inverter.
(2) Improvement of operation characteristics. It is excellent that no decline of efficiency for low load factor was seen, because the residential system has long periods of low power demand.
(3) Examination concerning thermal utilization. This system was designed with the specification of utilizing exhaust heat for domestic hot water. Improvement of performance is desired by utilizing this system for space heating and snow melting.
(4) Inspection of durability. Long-term durability is required for application of this system for residential use.

7. Conclusions

Experiments on the characteristics of heat and power generation of a PEFC (rated output: 1 kW) for a residential energy system were carried out. The following results were obtained.

1. Direct current electrical efficiency and heat recovery efficiency at LHV were quite high: 42.5 and 49.2%, respectively. The overall energy efficiency reached 77.9%.
2. In the experiments on the characteristics of partial load for load factors of 50 and 75%, almost no difference in overall energy efficiency was seen.
3. Measurement of heat recovery efficiency was carried out in the range between 5 and 30 °C of inlet water temperature for heat recovery. The lower the inlet water temperature became, the higher the heat recovery efficiency rose, by a small amount. On the other hand, electrical efficiency was almost stable.
4. In terms of start-up time, it took 60 min at cold start and 32 min at hot start. It took 28 min more to reach 1 kW.
5. Exhaust gas for a rated output operation was analyzed. The NO_x emission was quite low: 4.8 ppm.
6. Measurement of the characteristics of heat and power generation and a thermal performance test of a hot water tank were carried out at each load factor. Before the actual use for domestic hot water supply, thermal stratification in the hot water tank, time for heat saturation and the thermal performance were described.
7. Characteristics of heat and power generation for each load factor under continuous operation over 24 h were evaluated. It was proved that stable performance could be obtained. The relationship between the cumulative operation time and electrical efficiency was studied. The efficiency reduced by 5% of the initial value after a cumulative operation time of about 600 h.

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